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USING INTERNAL COOLANTS

II - SIX ALIPHATIC AMINES

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ADVANCE CONFIDENTIAL REPORT

KNOCK-LIMITED POWER OUTPUTS FROM A CFR ENGINE

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SUMMARY

An investigation was conducted to determine the knock-limited performance of AN-F-28, Amendment-2, fuel in a CFR engine when water solutions of the following aliphatic amines were added as internal coolants: monomethylamine, dimethylamine, ethylenediamine, diethylamine, triethylamine, and butylamine. All of the internal-coolant solutions consisted of 25 percent amine and 75 percent water except for monomethylamine and dimethylamine solutions, which had a slightly higher percentage of amine. The internal coolant-fuel ratio was 0.50 in most cases, but tests were run using water and water solutions of dimethylamine at a coolant-fuel ratio of 0.75. Comparison curves were run with no internal coolant and with water alone as an internal coolant. Experiments were conducted to determine the effect of increases in fuel flow and internal-coolant flow at constant air flow on the power output when the engine was operating at a high power level by means of the injection of dimethylamine-water solution.

For fuel-air ratios between 0.055 and 0.095, the addition of the diethylamine, triethylamine, and butylamine solutions decreased the knock-limited power. A knock-limited indicated mean effective pressure of 1024 pounds per square inch was obtained at a fuel-air ratio of 0.093 when using the dimethylamine-water solution at a coolant-fuel ratio of 0.75.

INTRODUCTION

An investigation is being conducted at the NACA Cleveland laboratory to determine the increase in knock-limited power obtainable by the use of internal coolants in a CFR engine. Preliminary tests reported in reference 1 have shown that water solutions of two aliphatic amines - monomethylamine and dimethylamine - were extremely effective in increasing the knock-limited performance of AN-F-28 fuel.

Additional tests (reference 2) of these two amines were therefore conducted over a wider range of operating conditions. A knock-limited indicated mean effective pressure of 967 pounds per square inch was obtained at that time at a fuel-air ratio of 0.092 when a dimethylamine-water solution (coolant-fuel ratio, 0.75) was used. Completion of the tests was prevented by the failure of the engine cylinder. The use of dimethylamine-water solution as an internal coolant might prove to be useful in the structural testing of various types of engines. Without encountering knock, cylinder pressures could be attained that are greater than most cylinders can withstand. The cylinder temperatures of such a test, however, would not be comparable with those of tests of fuel alone. Despite the increase in power experienced with the solution of dimethylamine and water, this solution has disadvantages for use in aircraft, one being high volatility. With the hope that a good antiknock agent can be found with favorable physical characteristics many additional compounds are to be tested.

The present report presents the results of tests of four additional compounds: ethylenediamine, diethylamine, triethylamine, and butylamine. The equipment was similar to that of reference 2 except that a stronger engine cylinder was used and certain changes were made in the ignition system. The test of a dimethylamine-water solution at 0.75 coolant-fuel ratio was repeated in the stronger cylinder because the previous data were incomplete. Tests of monomethylamine-water solution and dimethylamine-water solution at a coolant-fuel ratio of 0.50 were also repeated in order to obtain results comparable with the other amines. The drowning effect of the internal coolant and of the fuel were determined by increasing the liquid flow at constant air flow until there was a considerable decrease in power.

INTERNAL COOLANTS

The following seven internal-coolant solutions were tested:

- (a) Water
- (b) 32 percent by weight monomethylamine in water
- (c) 26 percent by weight dimethylamine in water
- (d) 25 percent by weight ethylenediamine in water
- (e) 25 percent by weight diethylamine in water
- (f) 25 percent by weight triethylamine in water
- (g) 25 percent by weight butylamine in water

All of the monomethylamine-water solution and most of the dimethylamine-water solution were obtained commercially. All other solutions were prepared at this laboratory from commercial grade amines. Distilled water was used for most solutions because tap water gave a cloudy precipitate when mixed with some of the amines.

When the values for this report were computed the heats of combustion of the amines were not taken into account. Therefore when the word "fuel" is used it indicates only AN-F-28, Amendment-2, fuel. The gross heats of combustion for the six amines in the liquid state obtained from reference 3 are as follows:

Amine	Gross heat of combustion (Btu/lb)
Monomethylamine	14,350
Dimethylamine	16,390
Ethylenediamine	10,210
monohydrate	
Diethylamine	17,810
Triethylamine	18,560
Butylamine	17,650

ENGINE AND AUXILIARY EQUIPMENT

The test setup was the same as that used in part I (reference 2) except for the engine cylinder and the ignition system. The cylinder used differed from a standard F-4 cylinder in four ways:

1. The inside corner of the combustion chamber between the roof and the side wall was machined with a 1/4-inch fillet.
2. The roof and the upper part of the side wall were increased in thickness from 1/4 to 3/8 inch.
3. The top 18-millimeter hole was slanted 25° to the vertical.
4. Two additional horizontal 18-millimeter spark-plug holes were provided.

Figure 1 shows cross-sectional views of this cylinder. Two spark plugs and a magnetostriction knock pickup were located as shown in the figure. The top hole was plugged.

The cylinder was held in a standard cylinder sleeve, and this sleeve was fastened to the crankcase with oversize, heat-treated studs. A heavy beam was placed over the engine and supports were connected to the top of the cylinder, minimizing damage to the engine and danger to the operators in case of a failure of the cylinder hold-down mechanism. The beam could take the entire upward thrust of the cylinder if the other fastenings failed.

TEST PROCEDURE

Tests were conducted using the seven internal coolants at a coolant-fuel ratio of 0.50 and using water and dimethylamine-water solution at a coolant-fuel ratio of 0.75. The following engine conditions were maintained for all tests:

Engine speed, rpm	2500
Compression ratio	7.0
Spark advance, deg B.T.C.	30
Inlet-air temperature, °F	250
Jacket temperature, °F	250

A single batch of AN-F-28, Amendment-2, fuel was used for both parts of the present series of tests (reference 2 and this paper).

Each internal-coolant solution was tested by injecting it intermittently into a modified F-4 intake manifold through a spray nozzle adjacent to the fuel nozzle. Each test consisted in determining the knock-limited performance for a series of points covering the normal range of fuel-air ratios. Most of the tests were carried into the lean and the rich regions until rough running was encountered, but the test of dimethylamine-water solution at a coolant-fuel ratio of 0.75 was cut short in the rich region by a limiting inlet-air pressure of 228 inches of mercury absolute. As soon as the data were recorded for each point, a test was made for afterfiring by turning off the ignition switch and observing the pressure trace on the oscilloscope. The ignition switch was left off until afterfiring had ceased or until 10 seconds had elapsed.

Experiments were also conducted to determine the effect of increases in fuel flow and internal-coolant flow at constant air flow on the power output when the engine was operating at a high power level by means of the injection of dimethylamine-water solution. The knock limit was first determined by setting the fuel and the coolant flows for a coolant-fuel ratio of 0.75 and then increasing the inlet-air pressure until knock was observed. Three factors were then varied in turn: (1) fuel flow; (2) coolant flow; and (3) coolant and fuel flow, maintaining coolant-fuel ratio of 0.75. In each case the variable was increased until there was at least a 10-percent decrease in the power, and data were recorded while the variation was being made. This procedure was repeated at three additional power levels.

PRESENTATION AND DISCUSSION OF RESULTS

The knock-limited indicated mean effective pressure, the indicated specific fuel consumption, the indicated specific liquid consumption, and the knock-limited inlet-air pressure plotted against fuel-air ratio are presented for AN-F-28, Amendment-2, fuel with and without each of the seven internal coolants. Tests of fuel alone were run on the same day as each group of internal coolants, and each curve sheet of figures 2 and 3 presents the results obtained nearest to the time of the other tests shown on that sheet. These tests of fuel alone are not in so close agreement as is usually expected, presumably because of the high powers to which the engine was subjected during some of the internal-coolant tests.

Figure 2 presents the data of the tests of water and of dimethylamine-water solution when added at a coolant-fuel ratio of 0.75. When water alone was used as the internal coolant, uneven firing was encountered for fuel-air ratios greater than 0.10. When

dimethylamine-water solution was used, afterfiring occurred at all points with fuel-air ratios less than 0.09; between fuel-air ratios of 0.045 and 0.083 the afterfiring maintained itself for at least 10 seconds. Autoadvancing preignition was not encountered. The test of dimethylamine-water solution was cut short by a limiting inlet-air pressure of 228 inches of mercury absolute when running at a fuel-air ratio of 0.093 and an indicated mean effective pressure of 1024 pounds per square inch. No engine failure was apparent while running at this power but, during the next overhaul, radial cracks were noticed in the cylinder worm wheel and these cracks presumably occurred during this test.

Results of tests made with the seven internal coolants when added at a coolant-fuel ratio of 0.50 are plotted in figure 3. Results with water solutions of monomethylamine and dimethylamine are presented in figure 3(a). The addition of either monomethylamine or dimethylamine to the water greatly improved the knock-limited performance. Monomethylamine seemed to be best in the lean region and dimethylamine in the rich. This trend was demonstrated in reference 2; the curves of reference 2 and those presented herein cannot be rigidly compared because of the different cylinders and ignition systems used. The injection of water alone gives a flat power curve with very poor performance in the lean region. No afterfiring was encountered with dimethylamine, but afterfiring was observed with monomethylamine for all points between fuel-air ratios of 0.05 and 0.10. Afterfiring lasting at least 10 seconds existed for fuel-air ratios between 0.06 and 0.09.

The test results presented in figure 3(b) are for water solutions of ethylenediamine, diethylamine, triethylamine, and butylamine when injected at a coolant-fuel ratio of 0.50. For fuel-air ratios between 0.055 and 0.095 the replacement of 25 percent by weight of the water with diethylamine, triethylamine, or butylamine decreased the knock-limited power relative to that obtainable with water alone. Inasmuch as this decrease in power covers most of the normal operating fuel-air-ratio range, these three amines cannot be considered as effective antiknock internal-coolant additives. The addition of ethylenediamine appears to permit a considerable increase in the knock-limited power. In the lean region near the stoichiometric mixture this increase is greater than that obtained with dimethylamine (fig. 3(a)), but in the rich region dimethylamine is much more effective. The results with ethylenediamine were quite erratic and not reproducible. This irregular behavior seemed to be peculiar to ethylenediamine. Two tests were run with this amine but only the results of the second test are shown.

Unpublished tests of 4 percent of each of various amines added to AN-F-28, Amendment-2, fuel with no internal cooling were made under the same conditions as the tests of this report. The results showed that triethylamine and butylamine were proknock agents for all fuel-air ratios, and that diethylamine was a proknock agent for fuel-air ratios less than 0.095. These results are in agreement with those of this report.

Table I summarizes some of the data of figure 3 and shows the relative knock-limited powers resulting from the addition of various amines to water when used as internal coolants.

The effects of excess fuel and internal coolant (in addition to that required to prohibit knock) on the power were studied with the aid of dimethylamine-water solution. A knock-limited point was first obtained in the rich region with a coolant-fuel ratio of 0.75, and the coolant and fuel flows were then varied either alternately or in proportion while the air flow was held constant. This procedure was repeated at three additional knock-limited points.

The results of these variations are presented in figure 4 where the indicated mean effective pressure is plotted against fuel-air ratio and against liquid-air ratio. In figure 4(a) dotted lines have been faired in to indicate where the power is approximately 90 percent of the power at the starting knock-limited point. The four knock-limited points vary somewhat from the curve of figure 2. This discrepancy might be caused by the fact that the knock-limited points of figure 4 were not run consecutively and were taken in a range where considerable scatter is usually encountered.

Figure 4(b) shows that a given increase in the coolant flow caused less drop in power than an equal increase in the fuel flow. Paradoxically, at a constant fuel-air ratio (fig. 4(a)) the curves of constant coolant-fuel ratio usually gave lower power outputs than did the constant coolant-flow curves, probably because the liquid flow was greater.

SUMMARY OF RESULTS

The results of tests of water solutions of six aliphatic amines as internal coolants in a CFR engine may be summarized as follows:

1. A 25-percent solution of diethylamine, triethylamine, or butylamine in water when used as an internal coolant resulted in a lower knock-limited power than that obtained with water alone for fuel-air ratios between 0.055 and 0.095.

2. A 25-percent solution of ethylenediamine in water when used as an internal coolant permitted a knock-limited power that was slightly greater in the lean region near the stoichiometric mixture and was considerably less in the rich region than the power obtained with the use of dimethylamine.

3. A knock-limited indicated mean effective pressure of 1024 pounds per square inch was obtained at a fuel-air ratio of 0.093 when using dimethylamine-water solution at a coolant-fuel ratio of 0.75. When this power was reached the air pressure in the intake to the engine was the maximum available from the laboratory intake-air system.

4. An excess of dimethylamine-water solution over that required to eliminate knock caused less decrease in the power than a similar excess of AN-F-28, Amendment-2, fuel.

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1. Bellman, Donald R., and Evvard, John C.: Knock-Limited Performance of Several Internal Coolants. NACA ACR No. 4B08, 1944.
2. Bellman, Donald R., Moeckel, W. E., and Evvard, John C.: Knock-Limited Power Outputs from a CFR Engine Using Internal Coolants. I - Monomethylamine and Dimethylamine. NACA ARR No. E4L21, 1944.
3. Kharasch, M. S.: Heats of Combustion of Organic Compounds. Res. Paper 41, Bur. Standards Jour. Res., vol. 2, no. 1, Jan. 1929, pp. 359-430.

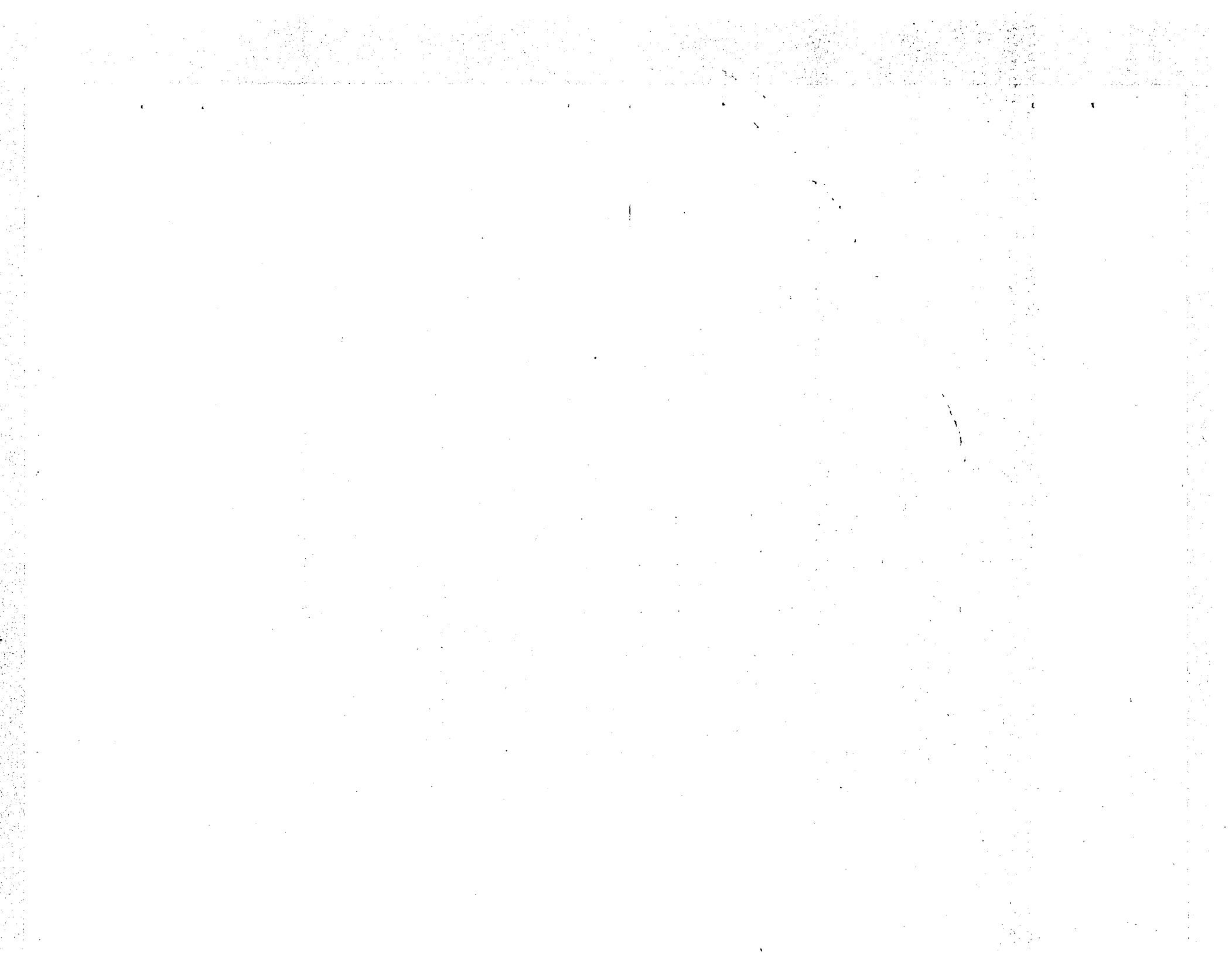
TABLE I - RELATIVE KNOCK-LIMITED POWERS RESULTING FROM
THE USE OF INTERNAL-COOLANT ADDITIVES IN WATER
AT A COOLANT-FUEL RATIO OF 0.50

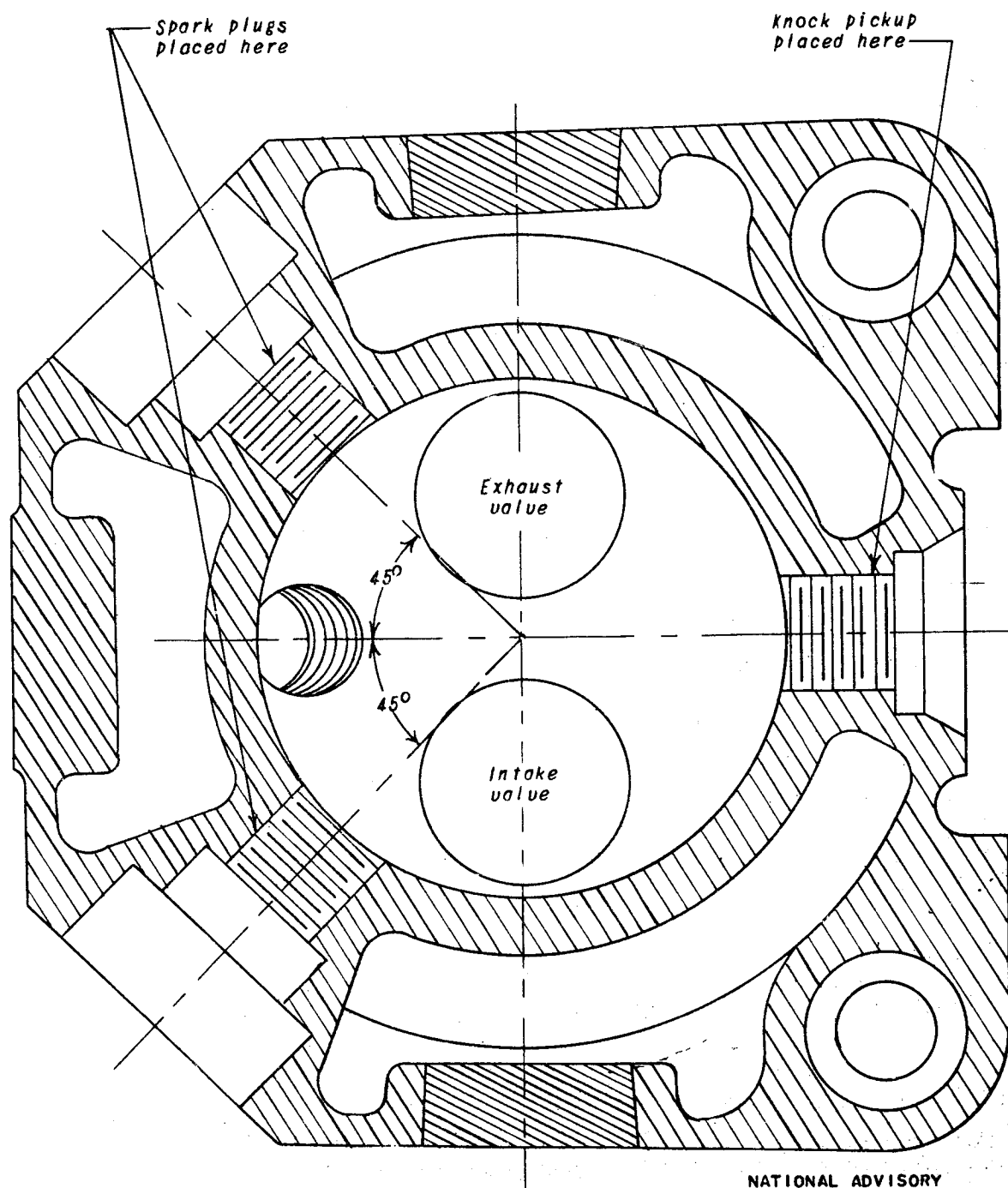
[CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F]

Internal-coolant additive	Percentage additive in coolant solution (wt)	imep (fuel + water + additive) imep (fuel + water alone)					
		Fuel-air ratio ^a					
		0.05	0.06	0.07	0.08	0.09	0.10
None	0	1.00	1.00	1.00	1.00	1.00	1.00
Monomethyl-amine	32	1.64	1.32	1.32	1.42	1.91	2.42
Dimethyl-amine	26	1.54	1.41	1.46	1.82	2.08	2.58
Ethylene-diamine	25	1.81	1.61	1.38	1.44	1.45	1.42
Diethyl-amine	25	1.09	0.86	0.77	0.92	0.96	1.07
Triethyl-amine	25	----	0.92	0.71	0.80	0.84	0.83
Butylamine	25	1.02	0.82	0.90	0.93	0.93	0.96

^aThe amines were not considered as fuels and their heats of combustion were neglected in computing the fuel-air ratios.

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(a) Bottom cross-sectional view.

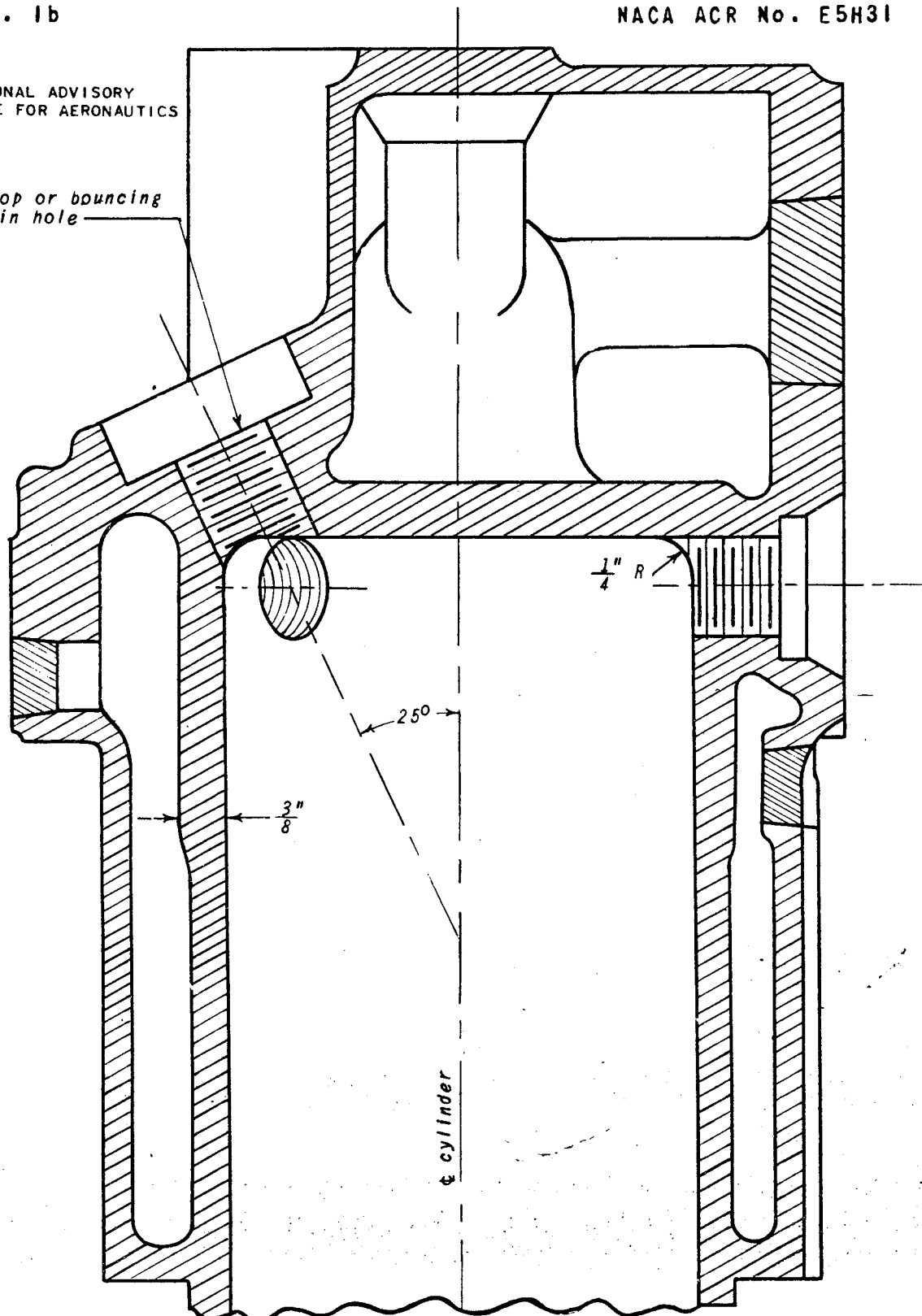
Figure 1. - Modified cylinder for a CFR engine.

Fig. 1b

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Top or bouncing
pin hole



(b) Side cross-sectional view.

Figure 1. - Concluded. Modified cylinder for a CFR engine.

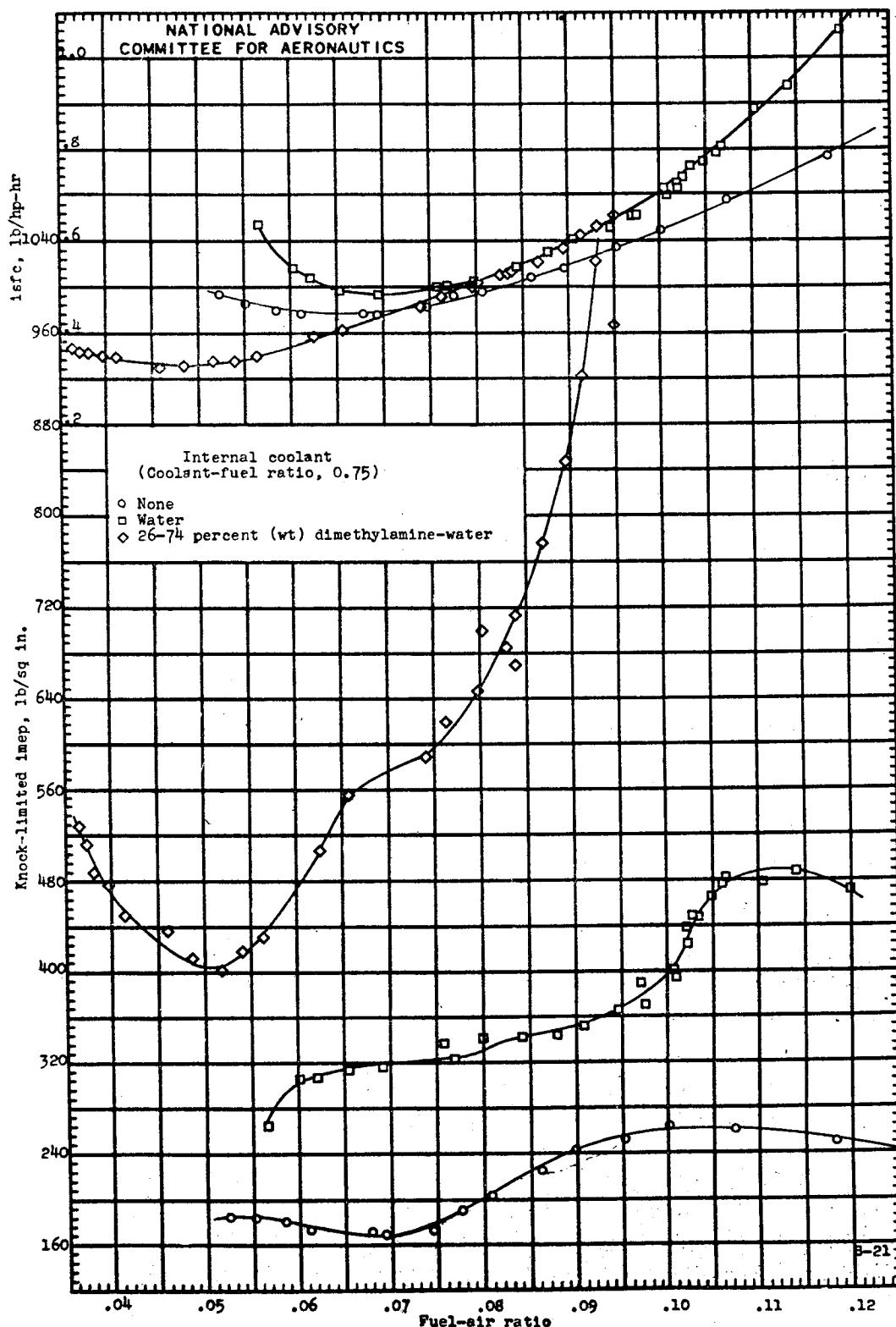


Figure 2. - Effect of internal coolants on the knock-limited engine performance with a coolant-fuel ratio of 0.75. CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.

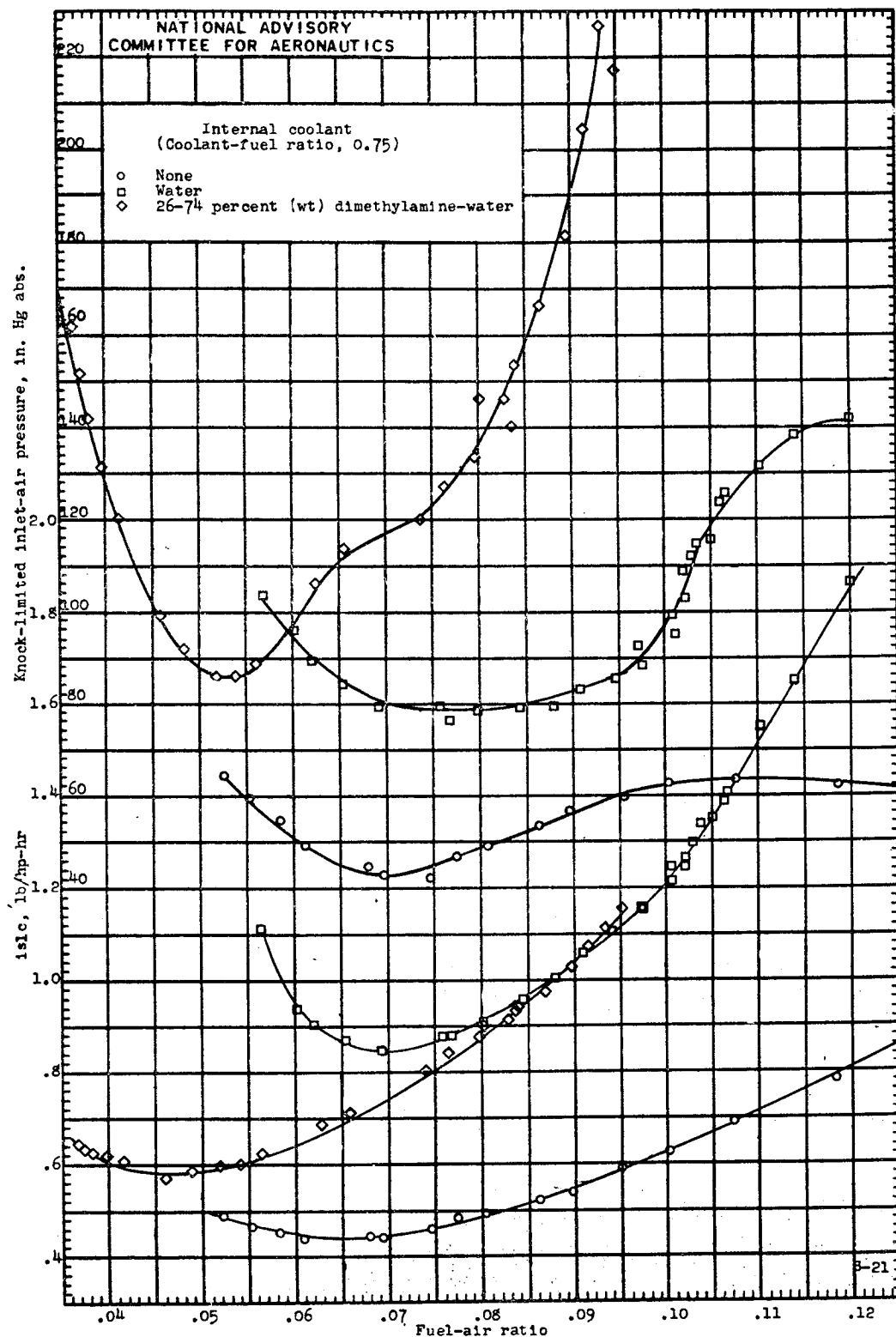
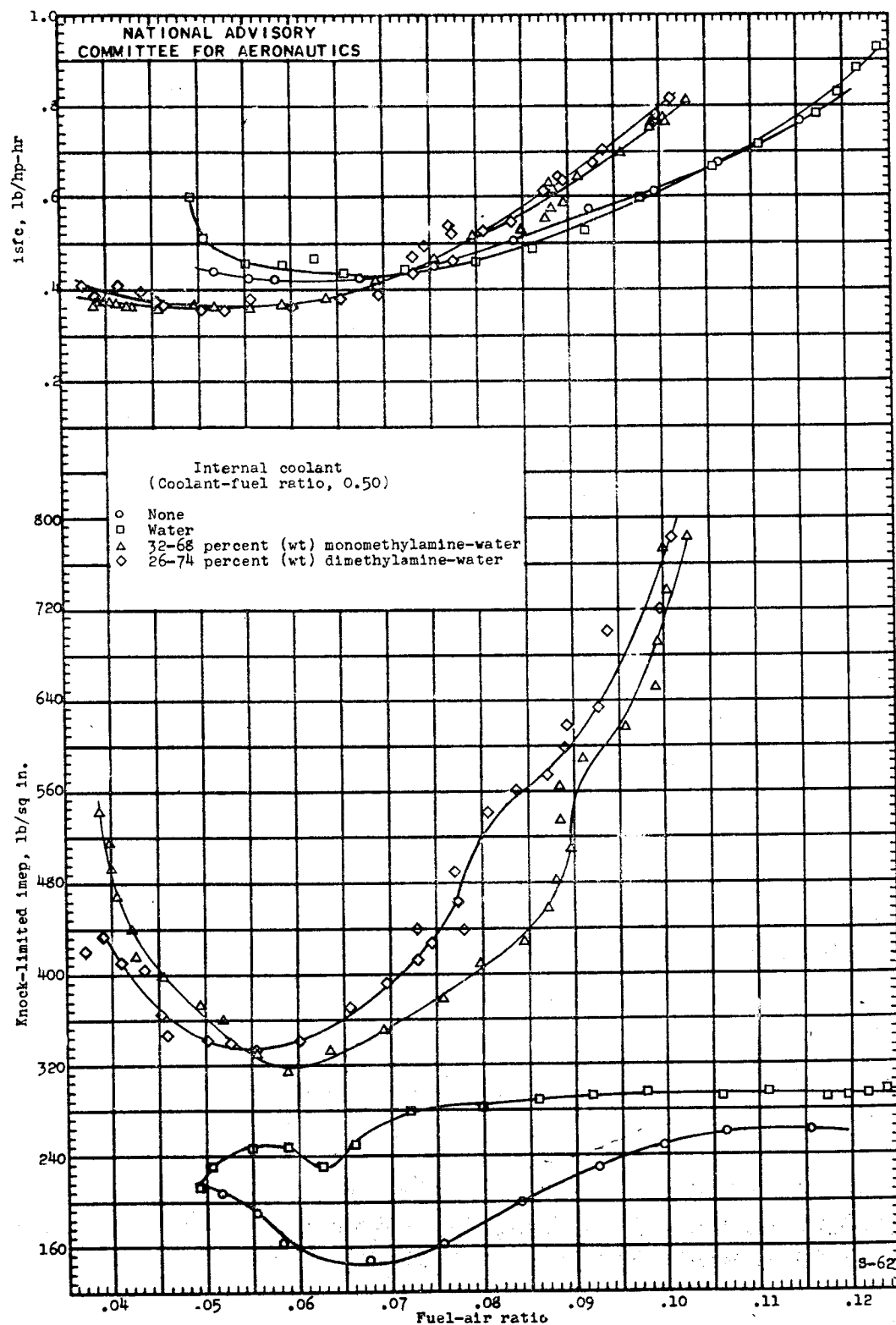


Figure 2. - Concluded. Effect of internal coolants on the knock-limited engine performance with a coolant-fuel ratio of 0.75. CFR engine; AN-V-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.

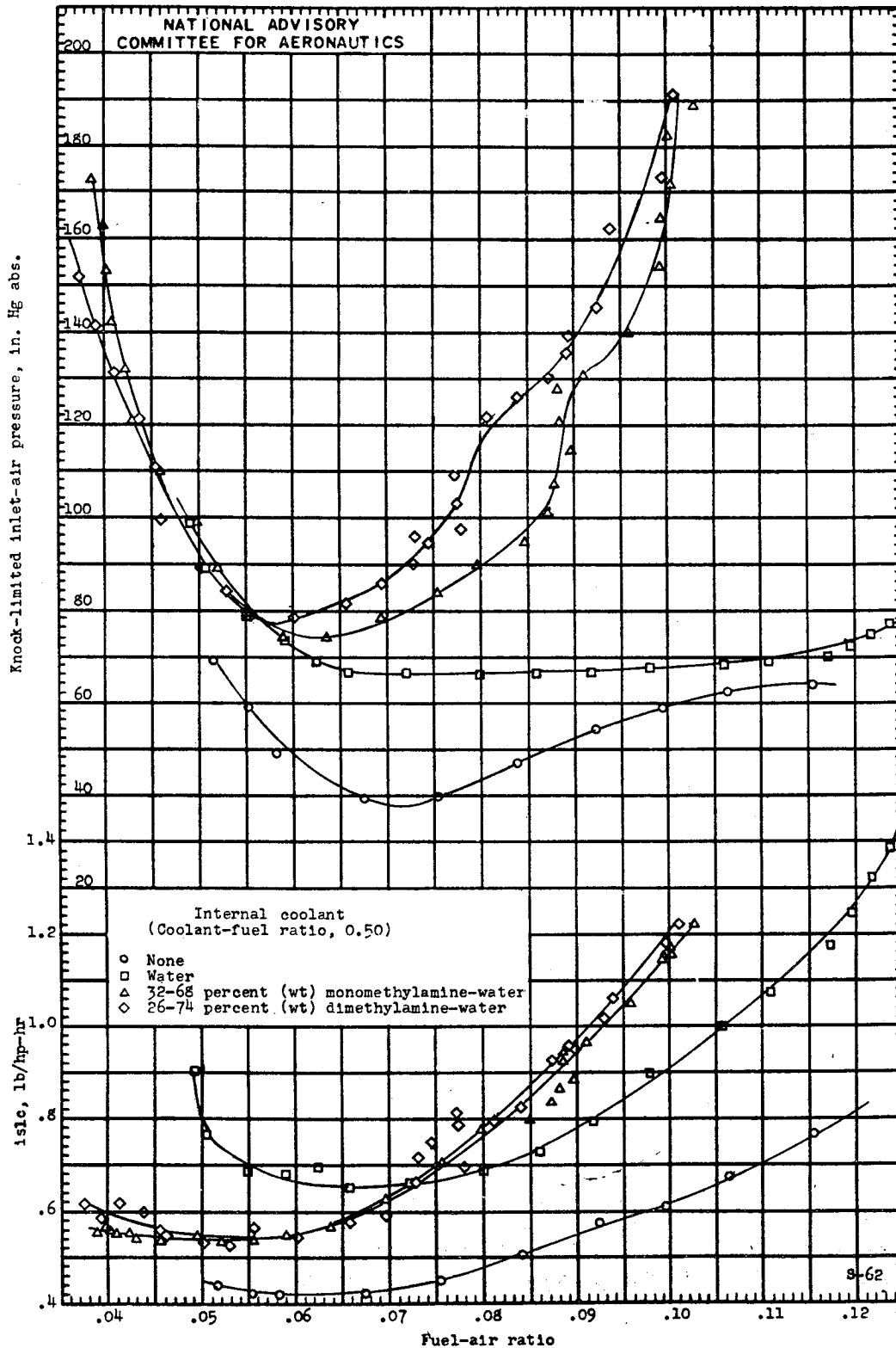


(a) Water and water solutions of monomethylamine and dimethylamine.
Figure 3. - Effect of internal coolants on the knock-limited engine performance with a coolant-fuel ratio of 0.50. CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.

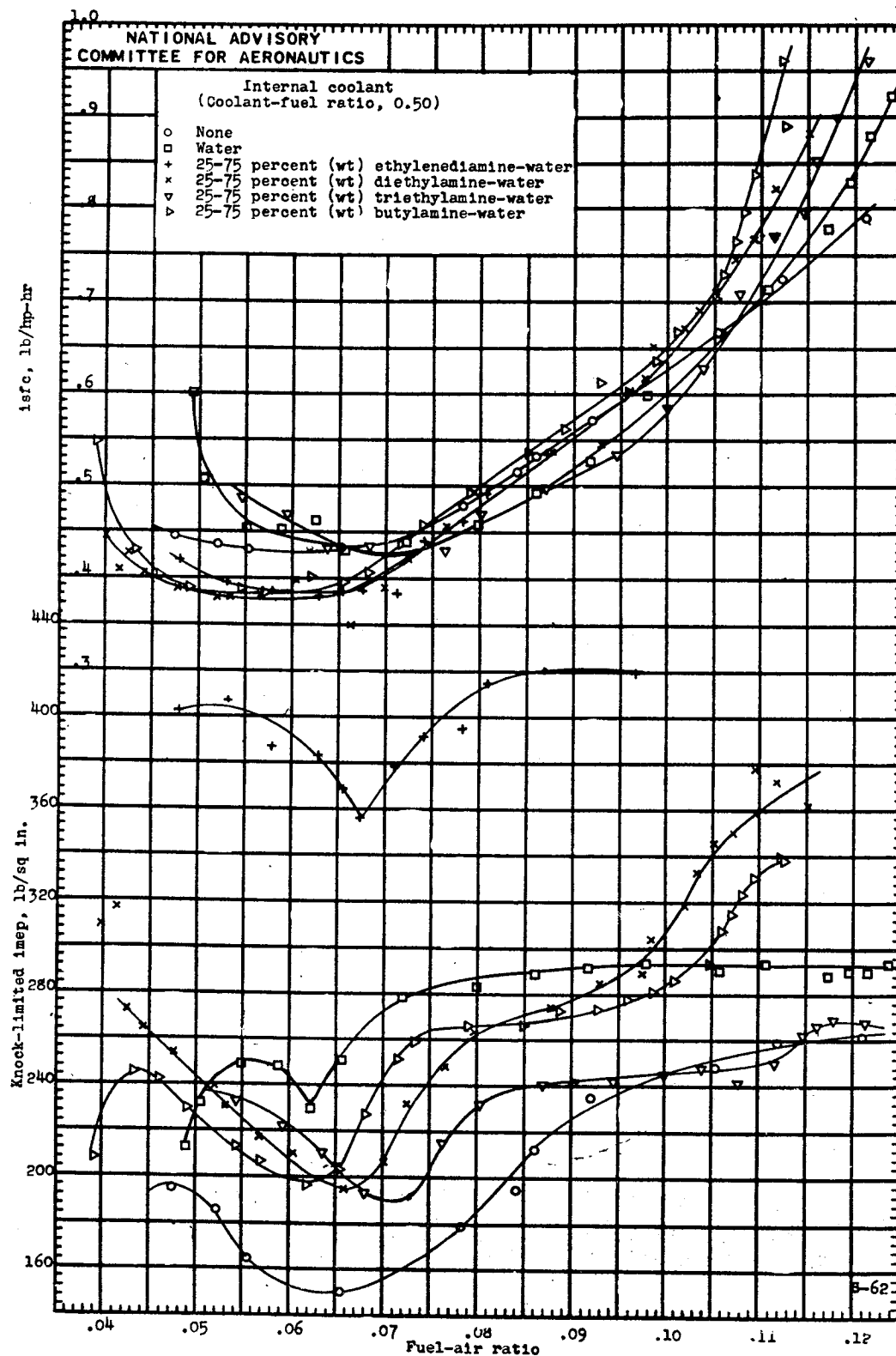
Fig. 3a concl.

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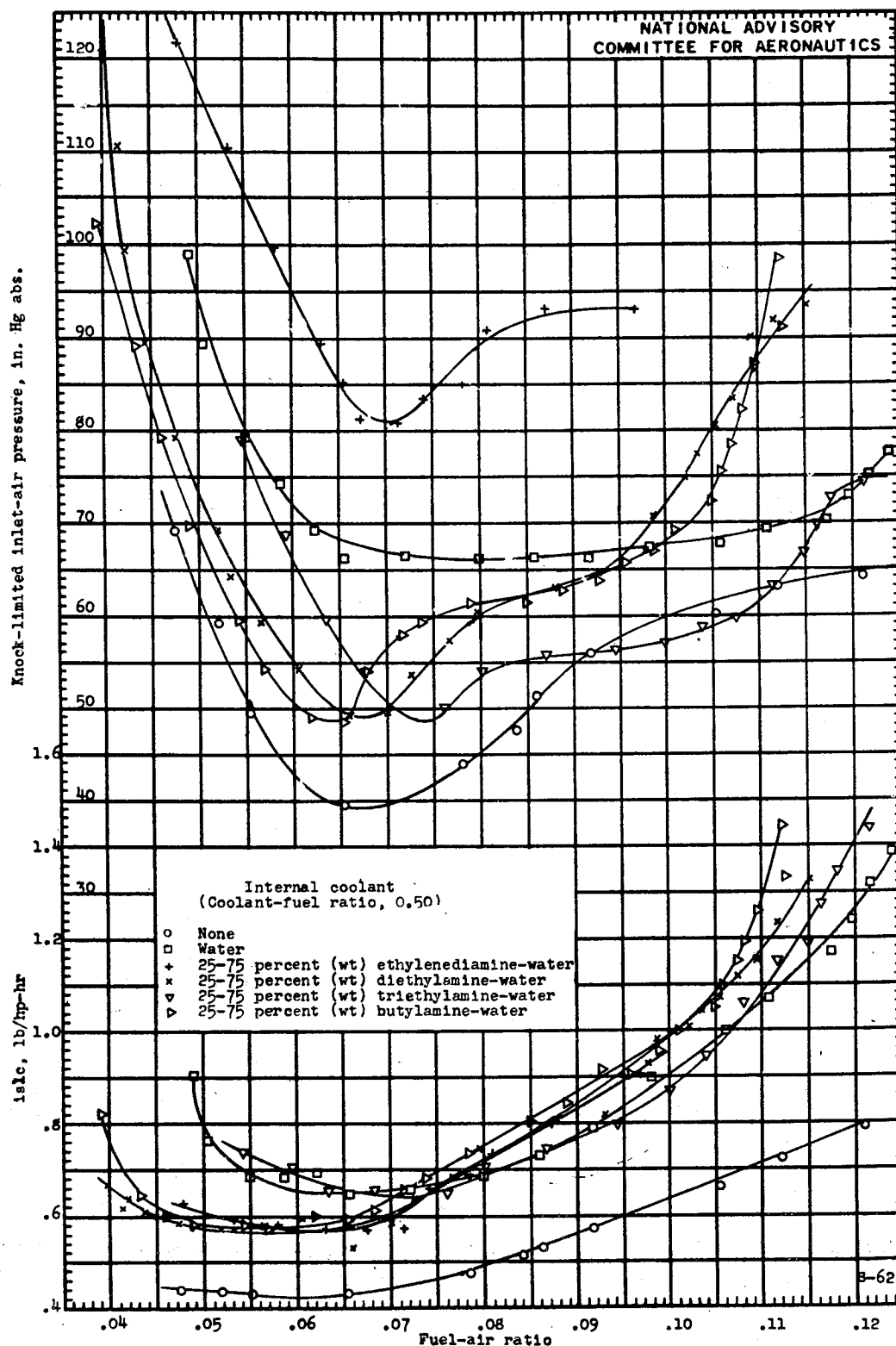
(a) Concluded. Water and water solutions of monomethylamine and dimethylamine.
Figure 3. - Continued. Effect of internal coolants on the knock-limited engine performance with a coolant-fuel ratio of 0.50. CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.



(b) Water and water solutions of ethylenediamine, diethylamine, triethylamine, and butylamine.
Figure 3. - Continued. Effect of internal coolants on the knock-limited engine performance with a coolant-fuel ratio of 0.50. CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.

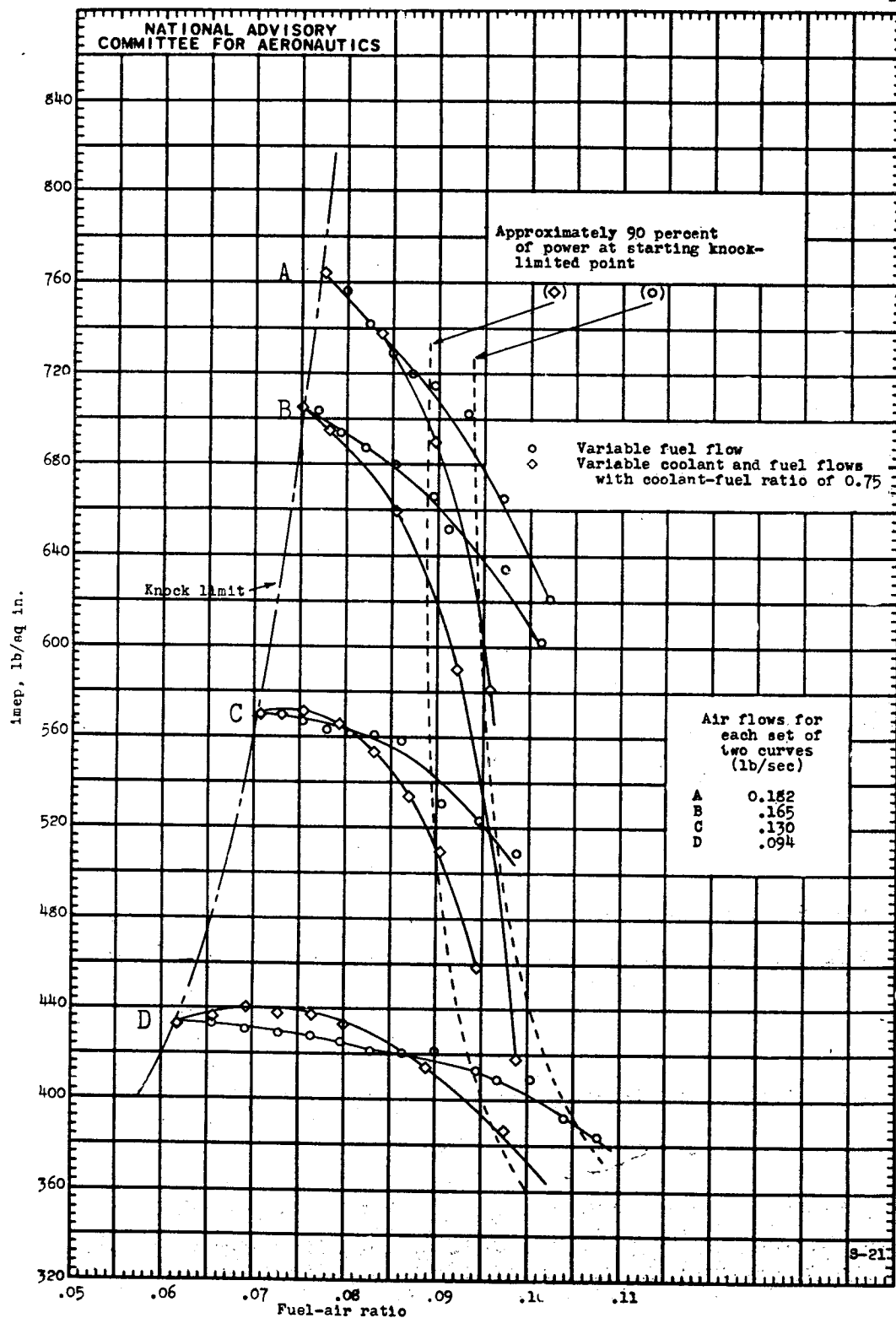
Fig. 3b concl.

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(b) Concluded. Water and water solutions of ethylenediamine, diethylamine, triethylamine, and butylamine.

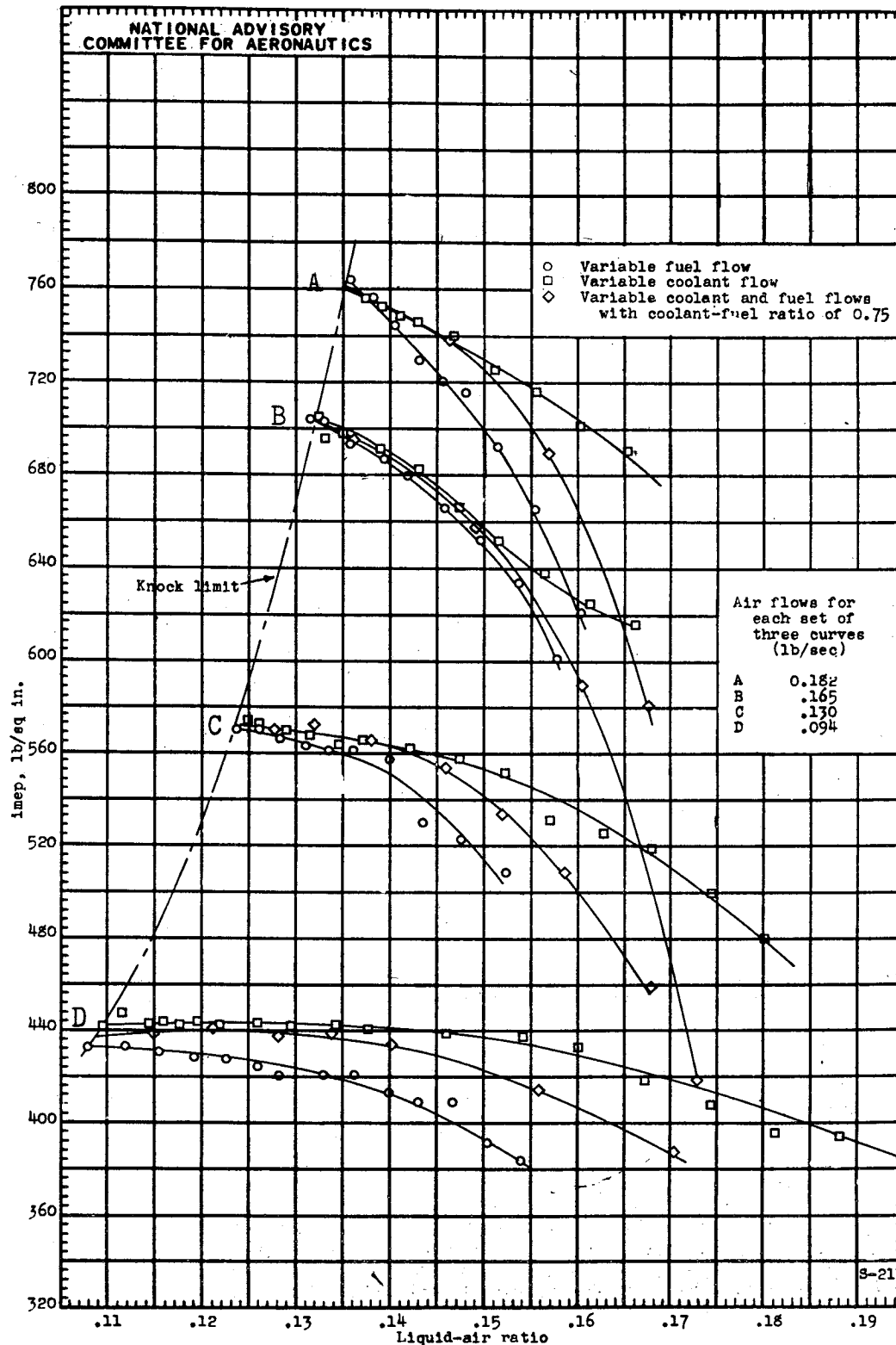
Figure 3. - Concluded. Effect of internal coolants on the knock-limited engine performance with a coolant-fuel ratio of 0.50. GFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.



(a) Indicated mean effective pressure against fuel-air ratio.
Figure 4. - Effect of variations in the fuel flow and coolant flow at constant air flow on the power output. Internal coolant, dimethylamine-water solution; CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.

Fig. 4b

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(b) Indicated mean effective pressure against liquid-air ratio.

Figure 4. - Concluded. Effect of variations in the fuel flow and coolant flow at constant air flow on the power output. Internal coolant, dimethylamine-water solution; CFR engine; AN-F-28, Amendment-2, fuel; engine speed, 2500 rpm; compression ratio, 7.0; spark advance, 30° B.T.C.; inlet-air temperature, 250° F; jacket temperature, 250° F.